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ELASTIC CONSTANTS OF ALUMINUM ALLOYS, 2024-T3510, 5083-H131 AND 7039-T64 AS MEASURED BY A SONIC TECHNIQUE

Ralph F. Benck
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August 1976

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This report presents the results of sonic tests performed on aluminum alloys, 2024-T3510, 5083-H131 and 7039-T64. Young's modulus, the shear modulus, Poisson's ratio and the velocity of sound are reported for the temperature range of 22° to 550°C.

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B

I. INTRODUCTION

The sonic tests reported herein were conducted in connection with the Core Materials Program of the Solid Mechanics Branch of the Terminal Ballistics Laboratory.

The purpose of the Core Materials Program is to characterize the mechanical behavior of armor and armor penetrator materials. This characterization should prove useful to the designers of armored vehicles and projectiles and will provide valuable input data for computer codes that model penetration processes.

The present report concerns itself with dynamic sonic testing of three aluminum alloys, used as either structural or armor material. The results reported herein consist of Young's modulus (E), the shear modulus (G), and Poisson's ratio (ν) as a function of temperature.

II. EXPERIMENTS

The measurement method is the resonance type i.e., when made to vibrate by a suitable transducer, the test specimen will resonate at a preferred vibrational frequency. This frequency is dependent upon the physical dimensions, density and modulus of elasticity of the sample. If the driving force is provided at a frequency which corresponds to the resonant frequency of the sample, then the amplitude of oscillation will be relatively high and "resonance" occurs. When this is achieved the sound waves introduced and reflected from the end of the sample retrace their original path and set up reinforcement with following waves. Quick and accurate determination of the frequency of these waves is relatively easy.

A. APPARATUS

The device used to measure the natural resonant frequencies of the test specimen is a precision, electronic, sonic test instrument: a Magnaflux Model SR-200 Elastomat, made by the Magnaflux Corporation of Chicago, Illinois. The frequency range of the oscillator is 600 Hz to 50 kHz with frequency stability reported to be within 0.01 percent.[1*] Piezoelectric transducers are used with frequency counting times of 10 sec. (± 1 count). For measurements made at elevated temperatures, a Magnaflux high temperature furnace (Model 204528) and furnace control console (Model 98176) are used. The maximum furnace temperature is 1000°C with a chamber temperature uniformity reported[1] to be ± 1.1°C for a six-inch center zone.

*References are listed on page 22.

B. SPECIMENS

Test specimens were machined into the form of nominally 6-inch long, 3/8-inch diameter rods. The physical dimensions of the specimens tested are listed in Table I. All the test specimens originated from heats of metal that previously had been the source of compression samples for quasi-static stress-strain curves.[2,3,4] The chemical analyses of the alloys are included in References 2,3, and 4.

TABLE I

PHYSICAL PROPERTIES OF 3/8-INCH DIAMETER SPECIMENS

Alloy	Sample Number	Length cm	Weight g	Apparent* Density g cm^{-3}
2024-T3510	1-1	15.22	30.2486	2.789
"	1-2	15.24	30.2423	2.785
"	1-3	15.24	30.2889	2.789
"	1-4	15.24	30.2855	2.789
5083-H131	2-1	15.24	28.9655	2.667
"	2-2	15.24	28.9706	2.668
"	2-3	15.24	28.9506	2.666
"	2-4	15.24	28.9240	2.664
7039-T64	3-1	15.12	29.4506	2.734
"	3-2	15.37	30.0490	2.744
"	3-3	15.24	29.8535	2.749

*Ratio of weight to specimen volume.

C. PROCEDURE

The specimen is suspended on a support cradle with a piezoelectric driver transducer attached to one end and a receiver transducer attached to the other. For measurements at elevated temperatures, the support cradle was placed in a uniformly hot zone of a furnace. Initially, the thin wire ends of the transducers were put in prick marks on the ends of the specimens and kept in place by flexure of the wire. At elevated temperatures the wires tended to sag and slip off the specimen. To prevent this, the transducer wires were spot welded to the ends of the specimens. This arrangement worked satisfactorily, except that the spot-weld generally broke at temperatures greater than 550°C.

The procedure used to measure the frequencies as a function of temperature is as follows: (1) Determine resonant frequencies at room temperature, (2) increase furnace temperature by either 25 or 50°C, (3) wait 25 minutes, (4) determine resonant frequencies at new temperature and (5) repeat steps 2 through 4 until 550 or 575°C is reached. The material properties were never remeasured on a sample that had been heated and cooled because these alloys were initially in a heat-treated condition. Additional tests were made on samples 1-4 and 3-1, which had previously been heated to 575°C. These determinations were of the relative effect of duration of heating at 400°C on the modulus and not of the absolute value of the modulus itself.

D. CALCULATIONS

The transducer excites the sample in three modes of vibration; transverse, torsional and longitudinal.

The frequency of the longitudinal mode of vibration, F^L, is.

$$F^L = \frac{V_L}{2} \cdot \frac{1}{L} \tag{1}$$

where L = Length of test sample

V_L = Velocity of sound = $\sqrt{E/D}$

E = Modulus of Elasticity

D = Mass Density

Substituting for E in Equation (1) and using the weight, P (in grams) for a circular rod, we have

$$E = 50.9122 \cdot 10^{-8}\, P \frac{L}{d^2} (F^L)^2 , \tag{2}$$

where E is in megapascals and L and d (the diameter of the rod) are in centimeters.

Expression (2) neglects laterial inertia. This effect has been evaluated by Rayleigh[5] who takes into account the effects of shape, size and Poisson's ratio. This contribution, in the form of a correction factor, K_1^L, is:

$$K_1^L = 1 + \frac{d^2}{L^2}\frac{\pi^2}{8}\nu^2 = 1 + \frac{d}{L^2} 1.2337\nu^2 \tag{3}$$

ν = Poisson's ratio

For circular cross-section specimens the transverse resonant frequency (F^T) is given by:

$$F^{T} = \frac{V_L \, d}{8\pi \, L^2} \tag{4}$$

Solving equation (4) for E, we have

$$E = 16.0623 \cdot 10^{-8}\left(\frac{P}{L}\right)\left(\frac{L}{d}\right)^4 \left(F^T\right)^2 , \tag{5}$$

A second correction factor, K_1^T, which takes into account the rotary inertia of the specimens[1], is:

$$K_1^T = 1 + \frac{d^2}{L^2} \left(3.092 + 0.854 \frac{E}{G}\right) - \frac{d^4}{L^4} 2.172 \frac{E}{G} \tag{6}$$

The torsional resonant frequency (F^{Tor}) of a circular rod is:

$$F^{Tor} = \frac{V_{Tor}}{2} \cdot \frac{1}{L} \tag{7}$$

where $V_{Tor} = \sqrt{G/D}$

G = Shear modulus

Solving Equation (7) for G, we have:

$$G = 50.9122 \cdot 10^{-8} \, P \frac{L}{d^2} \left(F^{Tor}\right)^2 \text{ (megapascals)} \tag{8}$$

The effect of thermal expansion of the test rod at elevated temperatures must be considered.[1] This is accomplished by multiplying Equations (2), (5), and (8) by the factor

$$F_{(t)} = \frac{1}{1 + at} \tag{9}$$

where a = coefficient of thermal expansion and

t = temperature.

Poisson's ratio, ν, can be calculated if E and G are known.

$$\nu = \frac{E}{2G} - 1 \tag{10}$$

Substituting Equations (2) and (8) in Eq. (10) one obtains a value for ν based on the longitudinal and torsional frequencies so that this equation may be written as equation (11).

$$\nu = \frac{1}{2}\left(\frac{F^L}{F^{Tor}}\right)^2 - 1 \tag{11}$$

Similarly, if Equations (5) and (8) are substituted in Equation (10) one obtains a value for ν based on the translational and torsional frequencies and is written as Equation (12).

$$\nu = 0.1577\left(\frac{L^2}{d}\right)\cdot\left(\frac{F^T}{F^{Tor}}\right)^2 - 1 \qquad (12)$$

The velocity of sound (cm sec^{-1}) can be computed from either the transverse or the longitudinal resonant frequency by the following relationships:

$$V_1 = 2LF^L \qquad (13)$$

$$V_T = 1.0812\ \frac{L^2}{d}\ F^T \qquad (14)$$

III. RESULTS AND DISCUSSION

Young's modulus (modulus of elasticity), E, the shear modulus, G, and Poisson's ratio, ν, for the three alloys, measured at room temperature (22°C) by the dynamic sonic method, are listed in Table II. The values presented are averages of measurements made on the specimens listed in Table I. Young's modulus and Poisson's ratio can be computed by using either the longitudinal or torsional resonant frequencies and values computed from both frequencies are presented. In computing E(T), E(L), ν(T) and ν(L) the corrections for inertia (expressions (3) and (6)) were applied.

TABLE II

MECHANICAL PROPERTIES OF 2024-T3510, 5083-H131 AND 7039-T64 ALUMINUM ALLOYS AT 22°C

	Sonic Tests					Quasi-Static Compression Tests[2,3,4]	
Alloy	E(T) GPa	E(L) GPa	G GPa	ν(L)	ν(T)	E GPa	ν
2024-T3510	75.44	74.93	28.3	0.321	0.304	76.1	0.321
5083-H131	72.76	71.73	27.1	0.318	0.300	71.5	0.320
7039-T64	70.43	69.63	26.1	0.320	0.300	71.8	0.326

Table II also includes corresponding data from quasi-static compression tests of specimens from the same heats of material as used in the sonic tests

In order to determine the time necessary for temperature equilibrium to be established in a heated specimen, the following experiment was performed. A sample was placed in the furnace and the resonant transverse frequency measured at room temperature. The furnace was then turned on and the transverse frequency monitored as the sample was heated and then held at a furnace temperature of 400°C. Results of two experiments of this type are shown in Figure 1 for one specimen each of 5083-H131 and 7039-T64.

Figure 1 shows that initially there is a rapid decrease in transverse frequency as the samples are heated from room temperature (20°C) to 400°C. The frequency levels off after approximately 20 minutes in the oven, and remains fairly constant for another 60 minutes at which time it starts to slowly increase. For the elevated temperature experiments reported herein, we waited 25 minutes between temperature increase and frequency measurement. Based on the results of Figure 1 and the fact that the maximum temperature increase was 50°C and not 380°C as shown in Figure 1, the 25 minute waiting period should have been adequate for the frequencies to have reached the level portion of their response curve.

Young's modulus, the shear modulus, Poisson's ratio and the velocity of sound for the alloys tested are presented as a function of temperature in Figures 2 through 10. All these quantities were corrected for thermal expansion and inertial effects by applying expressions 9, 3 and 6, respectively. Separate curves are presented for E(T), E(L), ν(T) and ν(L). The corrections reduced the differences between V(T) and V(L) to an insignificant amount and therefore the average velocities of sound are shown in Figures 4, 7 and 10.

As the temperature is increased the wave amplitudes at the resonant frequencies tend to decrease thereby making it difficult to locate those that were initially weak. This is especially true for the torsional frequencies and may explain the somewhat erratic behavior observed in Poisson's ratio at temperatures greater then 500°C.

There is not much information available in the literature concerning the temperature dependence of the elastic constants reported herein. The elastic constants of single crystal aluminum appear to vary smoothly with temperature up to near the melting point[6,7]. Garofalo[8] states that E and G for metals should vary linearly with temperature up to near the melting point, however in polycrystalline metals various types of discontinuities or deviations from linearity are found beyond certain critical temperatures. The experimental results for the aluminum alloys shown in Figures 2, 5 and 8 generally agree with the concept of linear dependence between E, G and temperature. One study of E versus temperature (up to 370°C) for 2024-T4 and 2024-T36 sheets[9] presents data similar to that shown in Figure 2.

Poisson's ratio for steels[8,10] is reported to remain constant or to increase slightly as the temperature is raised. Data on Poisson's ratio as a function of temperature for aluminum alloys are sparse but one study[11] on aluminum alloy, 6061-T6, shows a linear decrease in ν as the temperature is increased from 25° to 200°C.

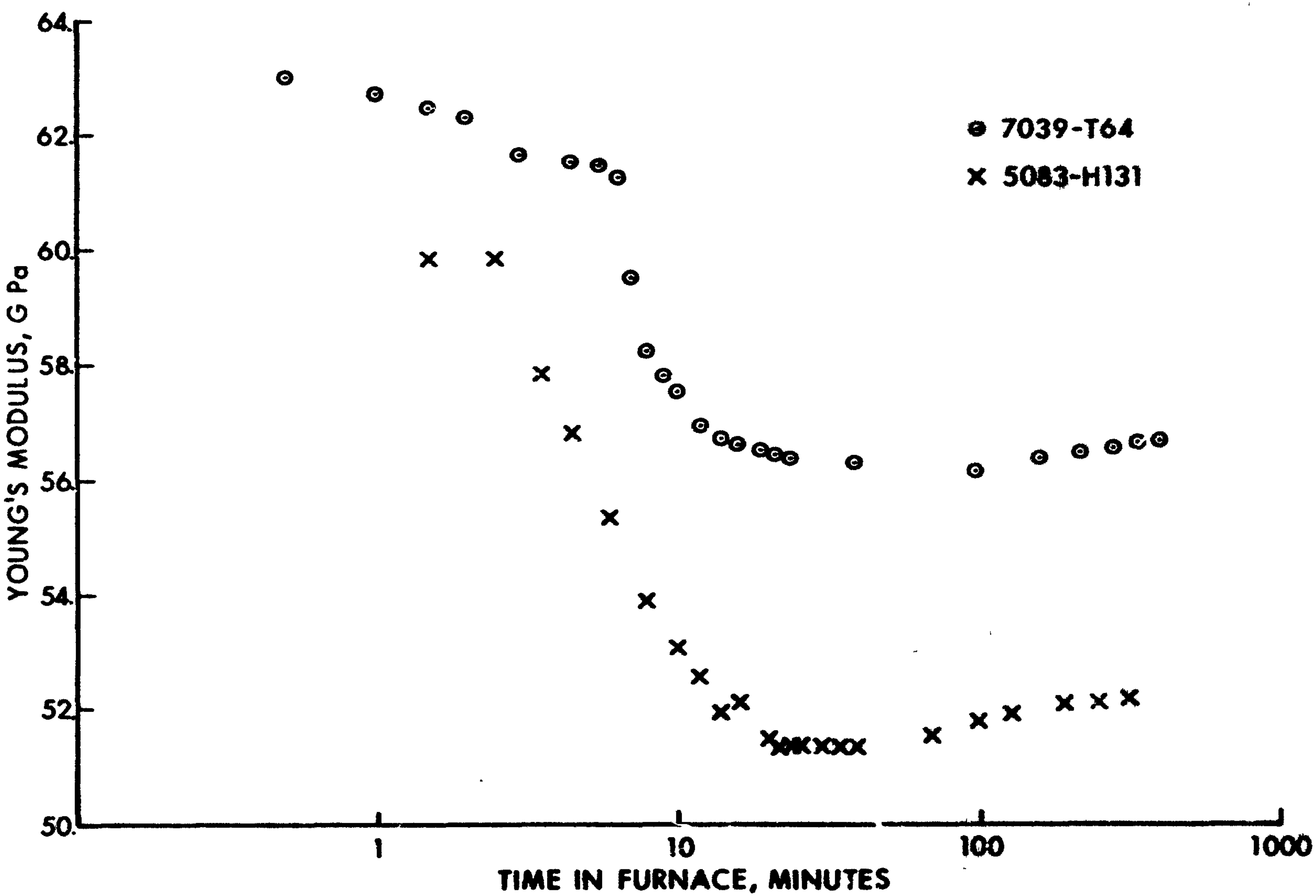

Figure 1- Young's Modulus as a Function of Time at 400°C for Alloys 7039-T64 (Sample 3-1) and 5083-H131 (Sample 1-4)

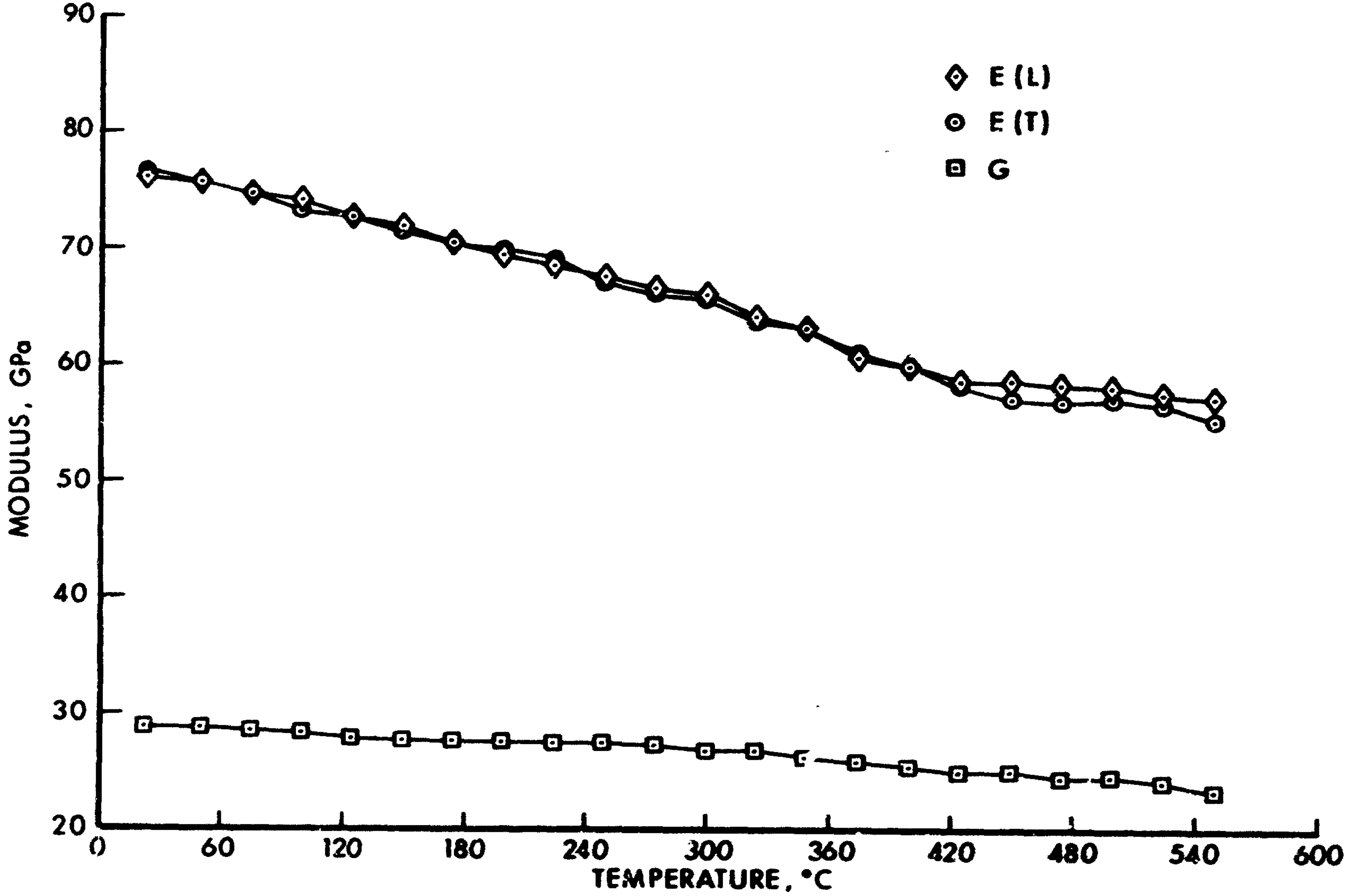

Figure 2. Young's Modulus and the Shear Modulus as a Function of Temperature for 2024-T3510 Aluminum Alloy

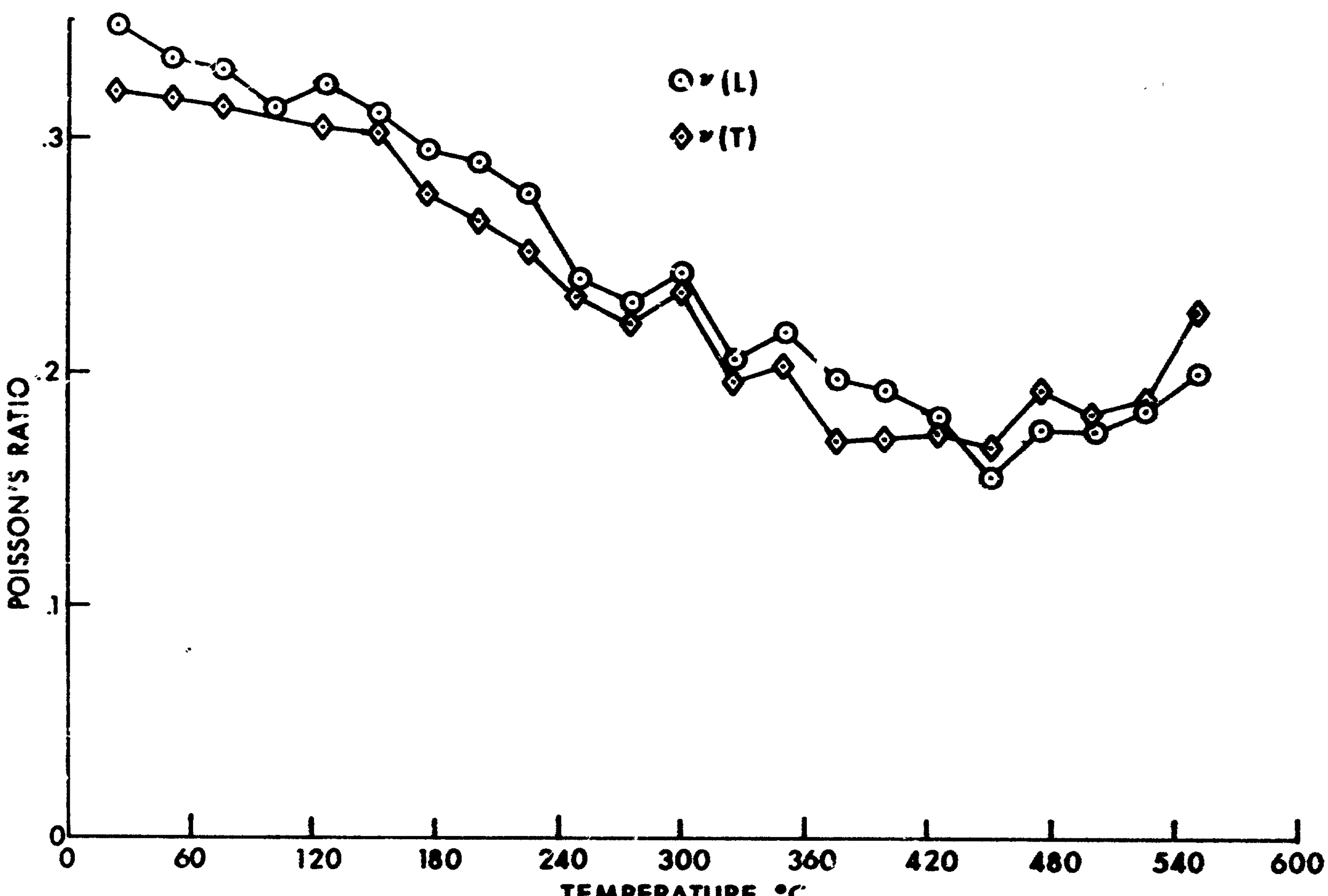

Figure 3 - Poisson's Ratio as a Function of Temperature for 2024-T3510 Aluminum Alloy.

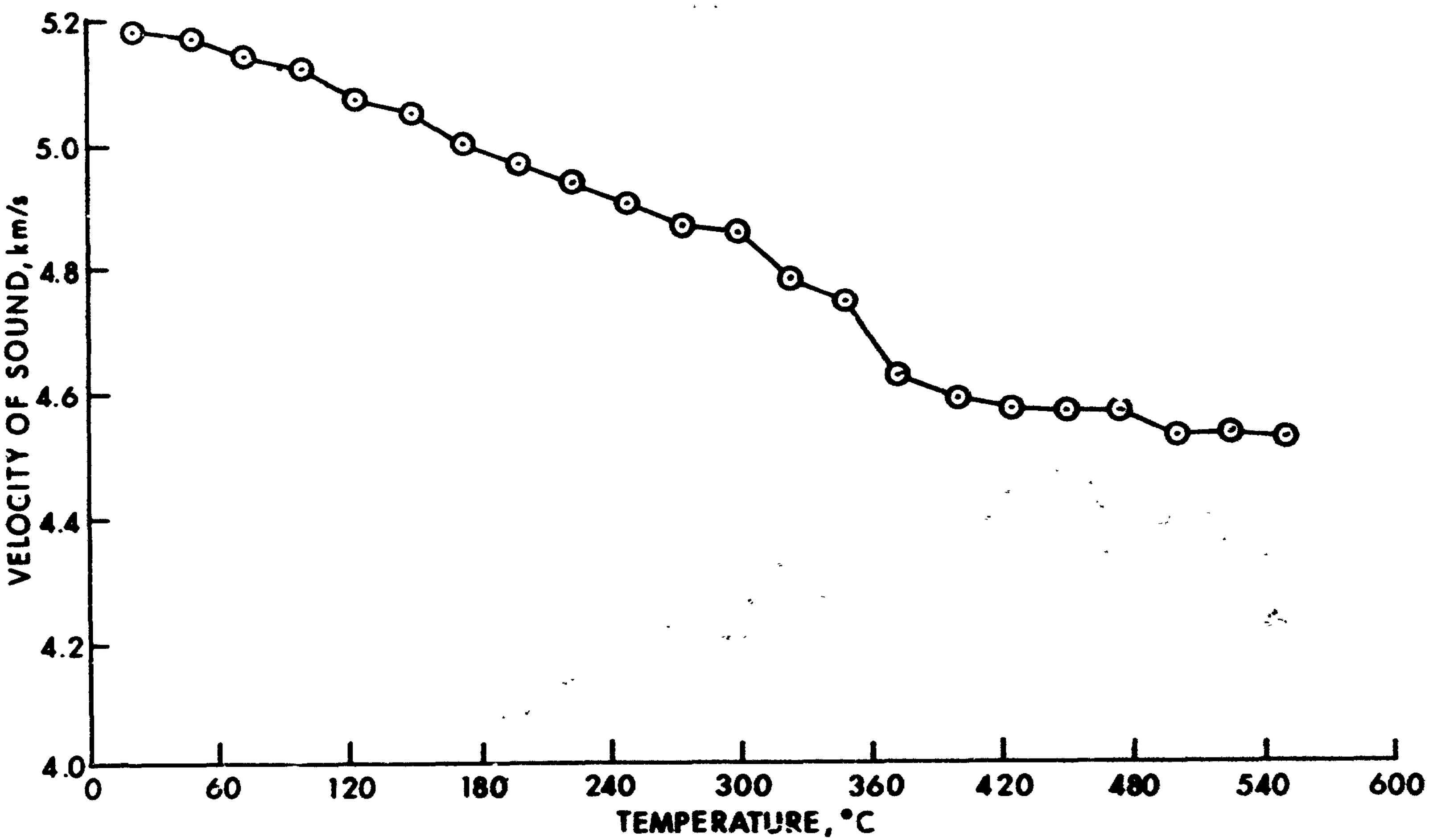

Figure 4- Velocity of Sound as a Function of Temperature for 2024-T3510 Aluminum Alloy.

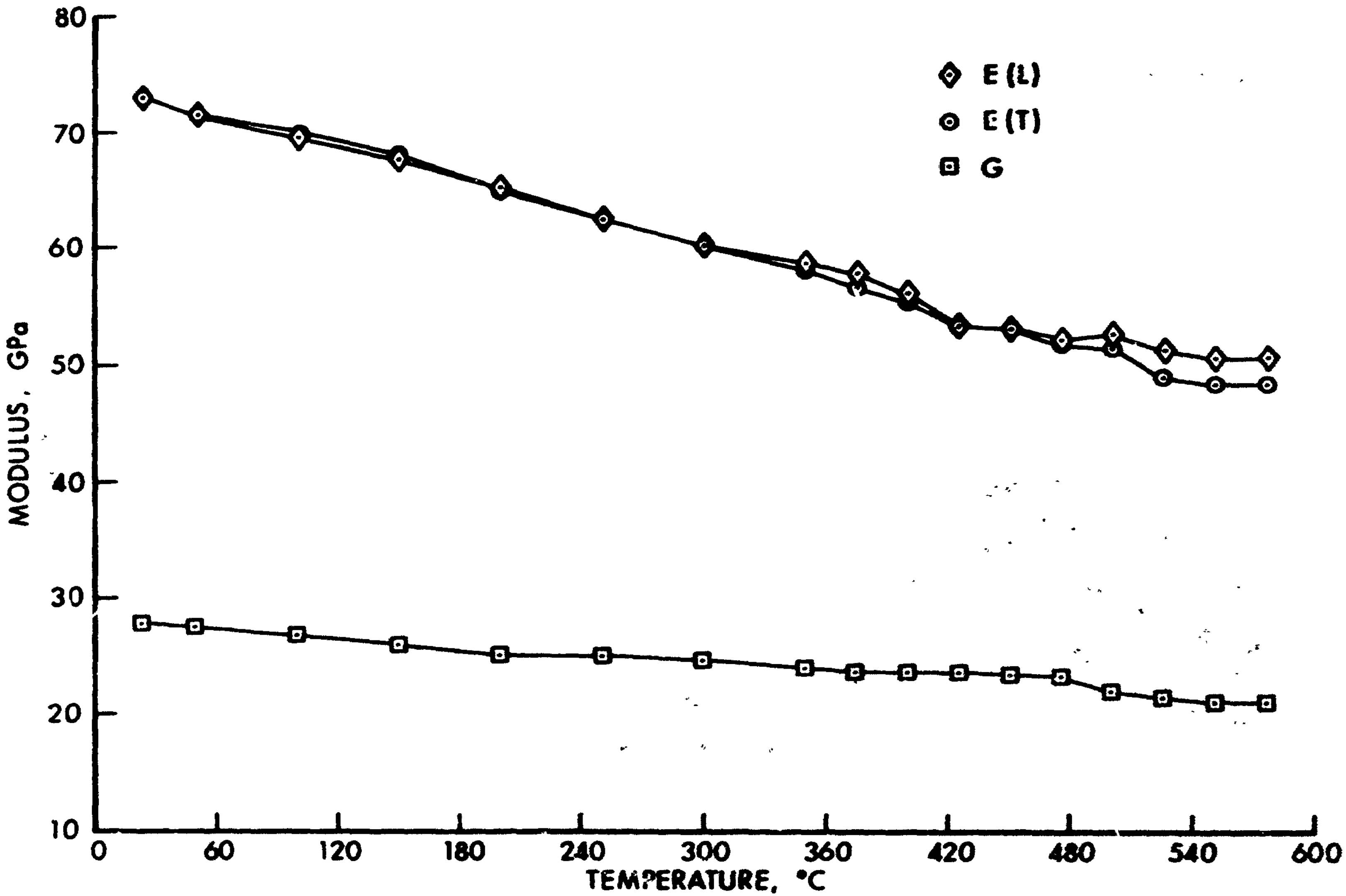

Figure 5. Young's Modulus and the Shear Modulus as a Function of Temperature for 5083-H131 Aluminum Alloy

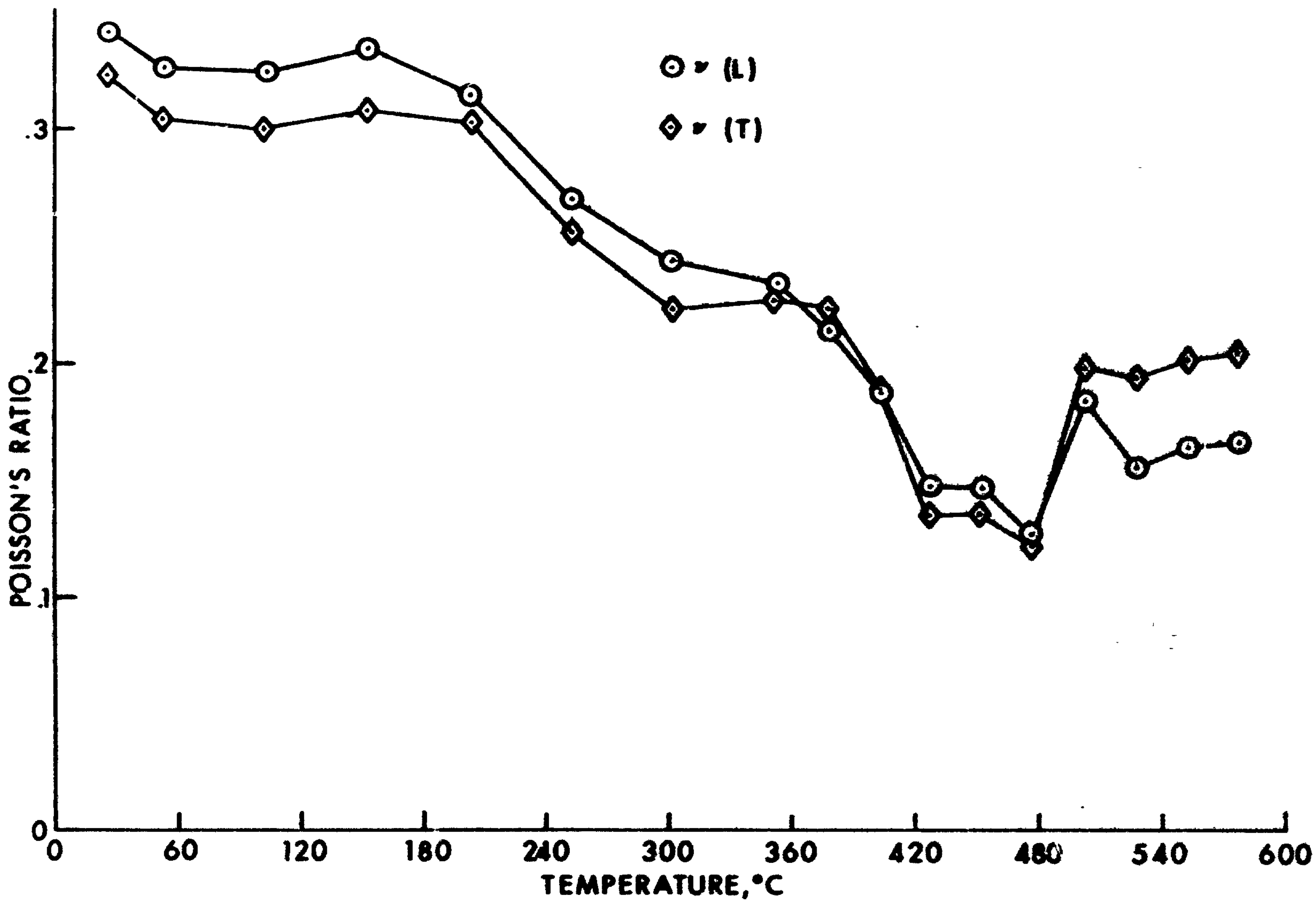

Figure 6-Poisson's Ratio as a Function of Temperature for 5083-H131 Aluminum Alloy.

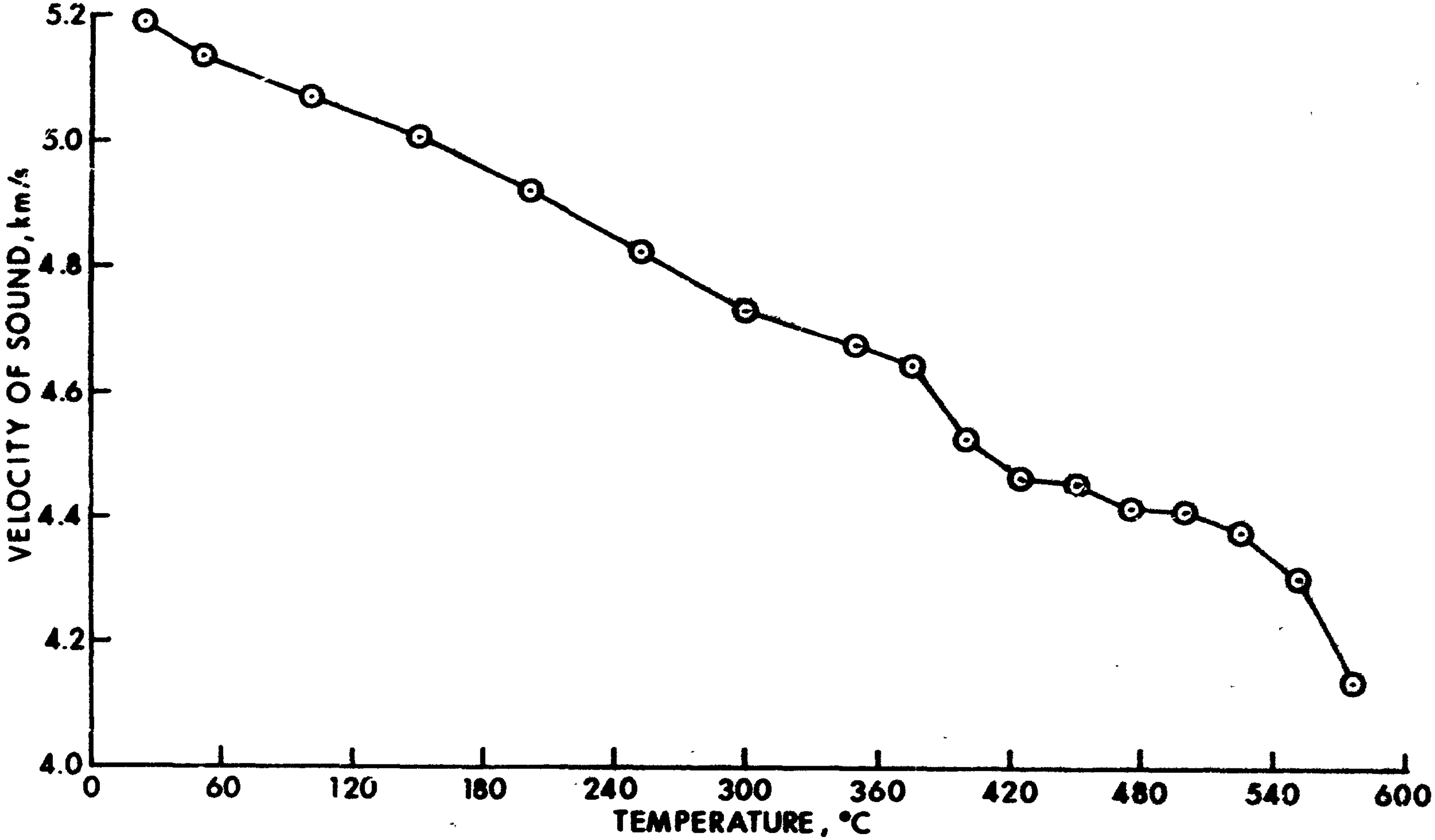

Figure 7- Velocity of Sound as a Function of Temperature for 5083-H131 Aluminum Alloy.

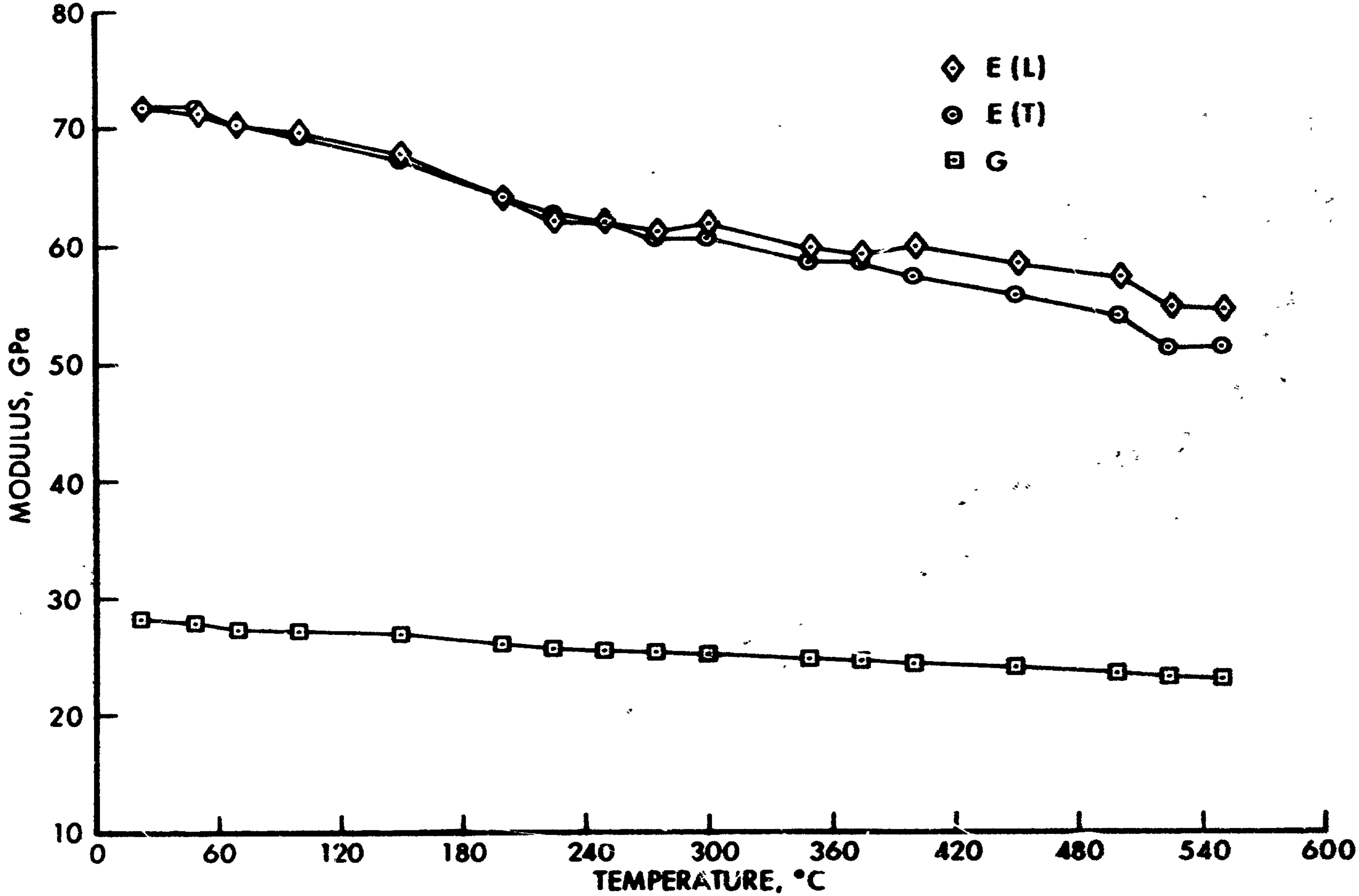

Figure 8. Young's Modulus and the Shear Modulus as a Function of Temperature for 7039-T64 Aluminum Alloy

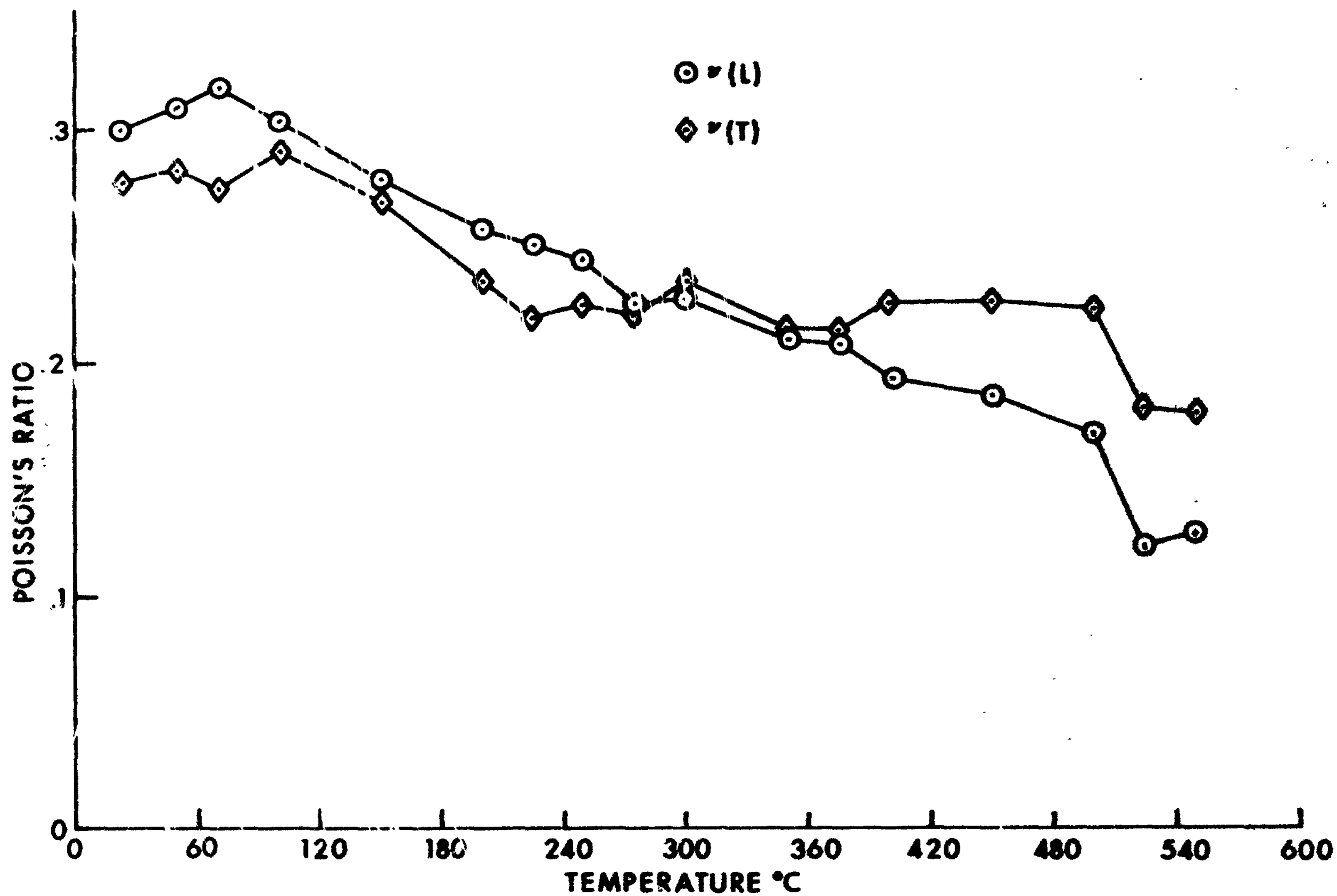

Figure 9- Poisson's Ratio as a Function of Temperature for 7039-T64 Aluminum Alloy.

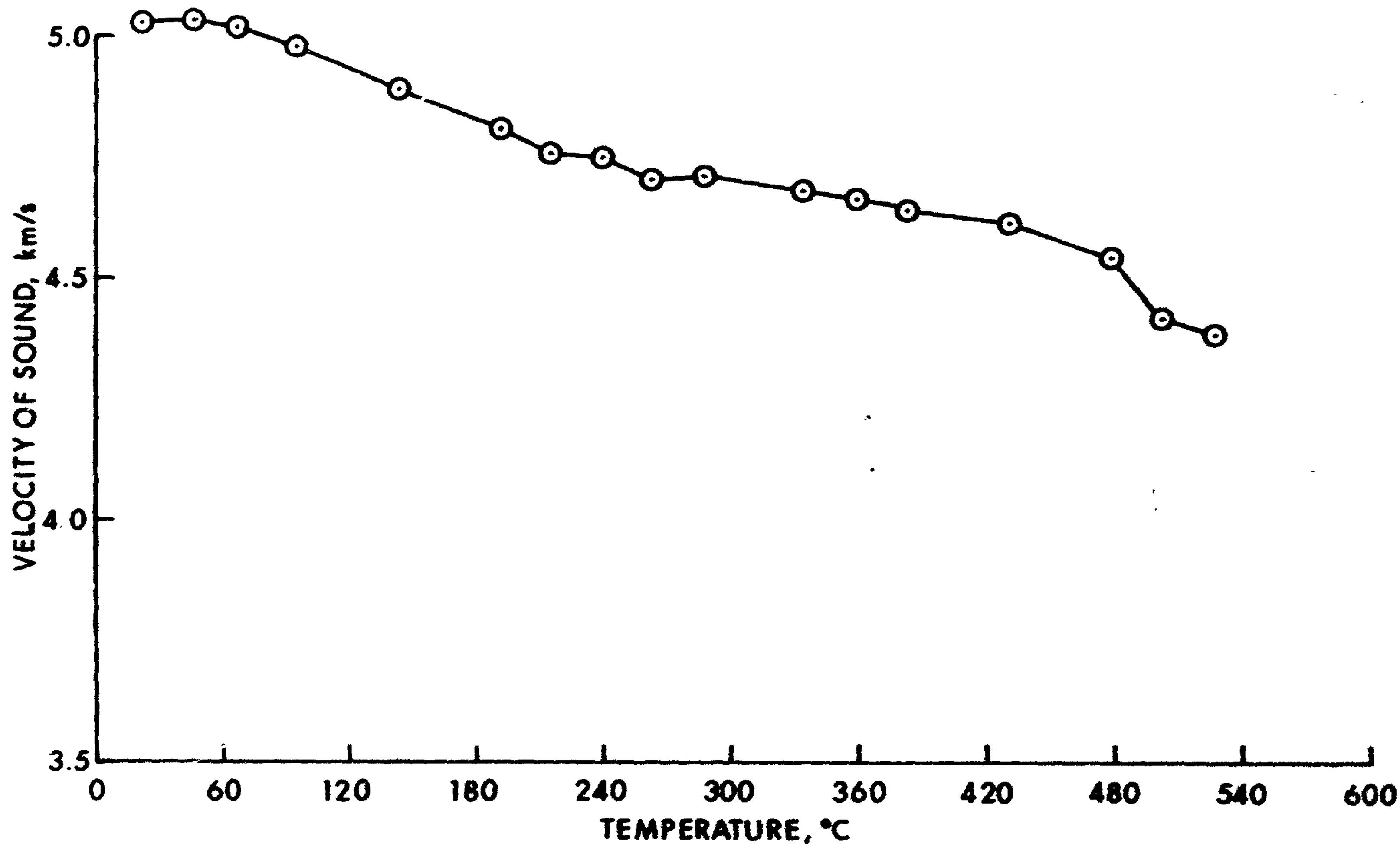

Figure 10-Velocity of Sound as a Function of Temperature for 7039-T64 Aluminum Alloy.

Our results for aluminum alloys, 2024-T3510 and 7039-T64 (Figures 3 and 9, respectively) show that Poisson's ratio decreases in a reasonably linear fashion as the temperature is increased from 25^{o} to 500^{o}C. Poisson's ratio for the 5083-H131 alloy (Figure 6), however; remains fairly constant from 25^{o} to 200^{o}C but then sharply decreases in the 200^{o} to 500^{o}C region. This is interpreted as a physical property of the materials tested not inconsistent with the other reported data in solids.

IV. CONCLUSIONS

A sonic method has been used to make dynamic measurements of Young's modulus, the shear modulus, Poisson's ratio, and the velocity of sound as a function of temperature for three aluminum alloys, 2024-T3510, 5083-H131 and 7039-T64. The results at 22^{o}C compare favorably with similar data garnered from quasi-static tests of specimens made from the same heats of material as used for the sonic tests.

In general, the elastic constants of these three alloys decreased as the temperature was increased.

REFERENCES

1. Instruction Manual for Model SR-200 Elastomat Instrument, Magnaflux Corporation, 7300 West Lawrence Avenue, Chicago, Illinois.

2. R. F. Benck, G. L. Filbey and E. A. Murray, BRL Memorandum Report in publication, "Quasi-Static Compression Stress-Strain Curves---IV 2024-T3510 and 6061-T6 Aluminum Alloys, Ballistic Research Laboratories, APG, MD.

3. R. F. Benck and E. A. Murray, Jr., BRL Memorandum Report #2480, "Quasi-Static Compression Stress-Strain Curves---III, 5083-H131 Aluminum", Ballistic Research Laboratories, APG, MD, May 1975. (AD #004159L)

4. E. A. Murray, Jr., BRL Memorandum Report #2589, "Quasi-Static Compression Stress-Strain Curves---II, 7039 Aluminum," Ballistic Research Laboratories, APG, MD, February 1976. (AD #B009646L)

5. J.W.S. Rayleigh, The Theory of Sound, Vol. 1, Dover Publications, New York, N.Y., 1945, p. 252.

6. D. Gerlich and E. S. Fisher, J. Phys. Chem. Solids, 30, 1197 (1969).

7. P. M. Sutton, Phys. Rev., 91, 816 (1953).

8. F. Garofalo, Trans. ASME, J. Basic Ed., 82, 867 (1960).

9. J. Wulf and W. P. Brown, Eds., "Aerospace Structural Metals Handbook", AFML-TR-68-115, Mechanical Properties Data Center, Belfour Stulen, Inc., 1974.

10. F. L. Everett, J. Appl. Phys., 15, 592 (1944).

11. J. R. Asay and A. H. Guenther, J. Appl. Phys., 38, 4086 (1967).

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